

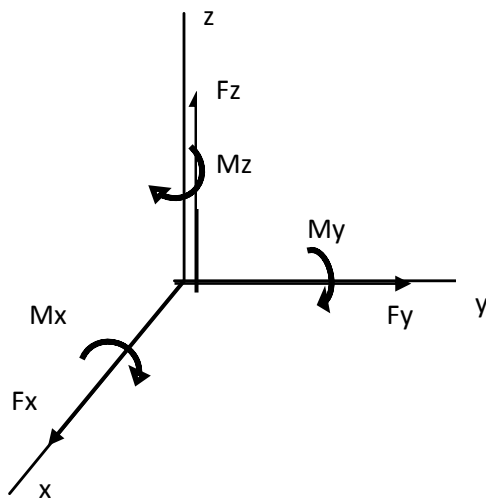
# Force measurement

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## Forces

### VECTORIAL ISSUES

In classical mechanics, a force is defined as "an action capable of modifying the quantity of movement of a material point". Therefore, a force has the attributes of a vector and is characterized by an application point, a direction and an intensity. Moreover, the set of forces applied to a point can be reduced to a system composed of 3 mutually orthogonal forces  $F_x - F_y - F_z$  and 3 moments  $M_x - M_y - M_z$  on these 3 axes. This group is known as the force torsor applied on this point.



This vectorial issue makes force and torque measurement a complicated matter. In practice, unidirectional and isolated pure forces do not exist. Other forces and moments always overlap and interfere with the force to be measured, and due precautions must be taken to eliminate them. In sum, two characteristics - application point and direction - need to be determined in order to measure a force, before applying techniques and methods to measure its intensity

It is equally useful to specify that a body at rest is subject to a set of forces and torques yielding a zero resultant.

### ACTION ET RÉACTION

This very same mechanism shows us the action and reaction principle, whereby "if a force is exerted on material point P2 by material point P1, then P2 will apply an equal force on P1 in the opposite direction". This is an important principle for the measurement of force. It is then necessary to take this other force into account, as well as the way it acts on the force measurement instrument, as it can have a great impact on measurement.

### ISOSTATISM

Isostatism refers to the contact between two solids with the strictly minimum number of points of contact. This simplifies the system of forces and moments involved in the contact and makes it possible to identify them. It therefore allows for better control of the system of forces present, resulting in better measurements.

### ACTION-AT-A DISTANCE

The theory of the elasticity of materials concluded that the further away strain deformations are located from the point where such strain is applied, the more linear the deformation will be. In other words, this

means that, the greater the precision sought, the more necessary it will be to have a force measurement instrument fitted with a strain gauge.

## Dynamometers

### GENERAL ASPECTS

The term **dynamometer** refers to an instrument used to measure force. It can also be used to refer to a testing machine capable of applying force of a given precision. Only the first of these meanings is referred to in this text.

A dynamometer is composed of a **transducer** comprising a metallic test specimen which receives the force to be measured and deforms elastically by the application of this force. In modern transducers such deformation (strain) is communicated to a miniature electric circuit attached to the test specimen, resulting in a modification of the electric resistance. This resistance variation is measured by the Wheatstone bridge method, whereby two legs of the electric circuit are supplied with an analog voltage, continuous or intermittent, and an analogue voltage variable according to the force applied to the dynamometer is collected between the two other legs in the circuit

The necessary equipment to supply voltage, collect and process the output signal and display usable values constitutes the electronic element connected to the transducer. Traditional electronic instruments - stabilized and multimeter supply - can be used. Transducer manufacturers have developed specific **electronic equipment** allowing to optimize settings, measurement conditions and precision.

The latest advances in the technique of dynamometers consist in integrating the electronic equipment associated to the digitalization of the signal and the transducer, so as to constitute a single device that, powered by 220 V, releases an **output digital signal** according to the force applied to the transducer.

When the relationship between the force applied to a dynamometer and the measurement of its output signal cannot be accurately determined by means of a calculation, it is necessary to **calibrate** the dynamometer, which consists in establishing the exact relationship between the force applied to a dynamometer - input - and the electrical signal it releases - output. In essence, the operation consists in applying forces that can be accurately measured to a dynamometer and registering the values provided by the electronic equipment connected to the transducer. This operation is generally performed by applying the protocol established by the international standard **ISO 376**. This standard provides for a classification of the dynamometer according to precision criteria. The results of the calibration of a dynamometer lead to the determination of a mathematical polynomial of 2nd or 3rd degree, which allows to calculate the value of the force applied to the dynamometer based on the indication provided by the electronic equipment. The formula allowing to calculate the level of uncertainty of this value is also part of the calibration.

Dynamometers are often used as the sensitive element of **weighing instruments**. In this case, the shape of the test specimen is determined so as to obtain an output signal that is exactly proportional to the mass of the specimen placed on the of the instrument loading tray.

## NOMINAL CHARACTERISTICS OF FORCE TRANSDUCERS

Given that a great majority of force transducers use strain gauges as a detecting element, this provides them with a set of nominal and metrological characteristics. The latter are introduced in the dynamometer calibration section. The main nominal characteristics defined in connection with the use of a transducer are described below.

### Applied forces

- The nominal applied force is that of the normal use of the transducer. A 10% variation of this load should not affect the validity of calibration.
- The maximum tolerated force without deterioration is the force that can be applied on the transducer without permanently altering its capacity to measure forces. The conservation of calibration results is not guaranteed for this load. It usually amounts to 130% of the nominal load.
- The breaking load is that causing the test specimen to break subject to a strain higher than the maximum strain tolerated by the material constituting the test specimen

### SENSITIVITY

The **sensitivity** of the transducer is the existing ratio between the voltage released and received by the transducer, which is loaded at the nominal force. It is expressed in mV/V. This value represents the maximum strain applied to the test specimen. The lower the sensibility, the weaker the level of strain applied to the transducer, and the better these metrological characteristics will be retained. Sensitivity values often range between 1.5 and 4 mV/V. A linear transducer translates into a constant sensitivity. For this to happen, the test specimen must have certain specific characteristics not found in a simple cylindrical rod generating slightly non-linear strains.

### EFFECT OF TEMPERATURE

Temperature affects the main elements constituting a force transducer. It affects :

- The test specimen, modifying its elasticity. This variation has a relative value of approximately 0.1% by degree for steels.
- The strain gauges, modifying their electric resistance.

The effect of temperature can be reduced by incorporating to the strain gauges components inducing in the measurement circuit a variation opposite to that caused by temperature. It is thus possible to reduce this influence by a factor higher than 5. But these compensations are generally only effective within a certain temperature range. Therefore, several temperature ranges should be considered. The reference temperature is that for which the metrological characteristics of the transducer have been established. It has currently been determined at 20 °C, the same as for all mechanic metrology fields.

- The **range of compensated temperature** on which the characteristics of the transducer are in fact obtained
- The **operative temperature range** on which the transducer can be used, without a guarantee that the metrological characteristics of the transducer will be respected, but without the loss of its nominal characteristics.
- The **storage temperature range** beyond which there is a proven risk of the permanent loss of the nominal characteristics of the transducer.

Finally, the effect of temperature on the transducer is represented by 2 ratios:

- **temperature-to-transducer sensitivity**, describing the variation in the sensitivity of the transducer according to temperature. It is expressed in the % of the value measured and in °C.

- **temperature-to-zero**, describing the variation of the signal released by the transducer at rest under the influence of temperature. It is expressed in the % of the transducer measurement range and in °C

## MEASUREMENT USING A DYNAMOMETER

Dynamometers can be used to measure an uniaxial force or a force system with several components. Such systems are composed either by the association of several single-component transducers within a structure defined for this purpose, or by using a test specimen of a specific type sensitive to different components of effort to be measured and capable of measuring the whole or part of the force torsor at one point.

Very powerful forces can be measured by associating several single-component transducers in parallel, the use of three transducers allowing for **isostatism**. The mechanical assemblies needed for such systems, often called transducer pyramids, must comply with specific requirements.

The verification of concrete testing machines requires the use of a very specific force transducer called strain cylinder.

Only the measures taken by a single-component transducer are analyzed.

In order to measure a force, it is necessary to previously determine two of its characteristics: its direction and point of application. It is also convenient to determine the precautions to be adopted, so that the use of the dynamometer does not modify the uniaxial nature of this force by introducing interfering components. In particular, mechanical pieces allowing for the transmission of the force to be measured to the transducer must filter the interfering efforts and must not cause them themselves. Measurement precision is directly conditioned by these connecting pieces.

The use of a force transducer requires that its effort axis be known, i.e., the axis at which the force must be applied to the test specimen. This axis must be materialized by accessible mechanical elements.

Two configurations must be distinguished, depending on whether the transducer is measuring tension or compression forces.

### Tension

The transducer's effort axis is generally materialized by the axes of the two threads or female threads at its ends. These must be co-linear and allow for an easy connection, of good mechanical quality, with the structure applying the load to the transducer and the structure holding it. The best solution is to use threads compliant with the ISO Standards, preferably within the first series of those not too thin, such as M 110x4 / M 64x4 / M 52x3 / M 30x2 / M20x1,5 / M12x1,75, and having tight geometric adjustment tolerances, of a 4h or 4H type, in order to limit to the minimum any float with the fixation pieces.

The second requirement consists in eliminating the influence of interfering forces and torques on the measurement performed on the axis of the transducer. As long as the transducer is fitted with two threads at its ends, this is an easy procedure, performed by using two radial ball-and-socket nozzles fixed on both sides of the transducer. These fittings define two rotation centres which will only allow the transfer of forces exerted on the axis connecting these two centres. Provided that these fittings are in good condition and mounted on the transducer with a reduced level of mechanical float, they guarantee decoupling, as they eliminate any action operating beyond the ball-and-socket fitting and allow for an improvement of measurement by a 10 factor. For very big loads, it proves impossible to use ball-and-socket fittings. In this case, it is necessary to take specific precautions in order to ensure that the force to be measured is strictly uniaxial and goes through the transducer effort axis. Measurement precision of is nevertheless not as high.

## Compression

Three fundamental difficulties arise: the materialization of the transducer effort axis, the contact surface permitting the application of the force being measured to the transducer, and the effect of the structure reaction on the transducer.

Materialization of a compression transducer effort axis is less evident than that of a tension transducer. If the transducer has a flat base fitted with a good mechanical quality bore centred on the geometric axis of the test specimen, it is known that the transducer effort axis is the perpendicular to its bottom plate going through the centre of this bore. In this case, the application point of the force to be measured on the opposite plate of the transducer must be located on this axis. The bore on the bottom plate is replaced by a machining of exactly the same external diameter as this plate if it is cylindrical.

Taking the resistance of the material into account, it becomes evident that the application of the force being measured to the transducer cannot be fixed on one point. It is necessary to have a contact surface. This surface must be as small as possible and avoid to the greatest possible extent the generation and transmission of interfering forces and torques. The best solution is to fit the test specimen of the transducer with a spherical cap at the end, on which a flat support surface is placed. This system produces a very effective decoupling. The main difficulty relates to the selection of the radius of the spherical cap and to the mechanical characteristics of the support piece, specifically its resistance to compression and its hardness. Contact with the transducer is then reduced to a point which becomes a surface during the application of the force, this process being irreversible. The geometry of the support piece must allow for a precise positioning of this piece on the structure generating the force being measured. If the transducer is not fitted with a spherical cap, it is generally possible to apply an appropriate dimension, which assembly conditions must be determined.

High-capacity compression transducers are sometimes fitted on the top with axial ball-and socket fittings of a large radius. Such equipments are useful to limit the effect of the non-parallelism of the surfaces, but they do not, however, ensure the actual filtering of interfering forces.

According to the laws and principles of mechanics, the bottom plate of a compression transducer placed on a surface receives from it an equal opposite force to that applied on the top of the transducer. This point is often overlooked and causes several measurement errors. The supporting surface of the compression transducer greatly conditions the strain induced on the test specimen and used to measure the force applied to the transducer. The transducer must be placed on a base in contact with the whole supporting surface. This piece must be perfectly flat and as rigid as possible. The hardness of the material used must be comparable to that of the transducer. Also, a precise positioning of the transducer on this base often allows to ensure that the force being measured goes through the transducer effort axis. If the transducer is clamped by screws on a specific mounting base or a support surface, the tightening torque of this screw is to be defined and respected.